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Period-doubling of gain-guided solitons in fiber lasers of large net normal dispersion

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Abstract

We report on the experimental observation and numerical simulations of period-doubling of gain-guided solitons in an erbium-doped fiber laser operating in the large net normal cavity dispersion regime. Features of the solitons before and after the period-doubling bifurcation are studied. Our results suggest again that period-doubling is an intrinsic feature of the mode-locked soliton lasers, which is independent of the mode-locked pulse property.

Passively mode-locked fiber lasers are well-known as an attractive source of ultrashort optical pulses. In fact, they are also an excellent test bed for the nonlinear dynamics. The pulse propagation in the laser cavity is governed by the extended Ginzburg–Landau equation (GLE), which is itself a paradigm equation of the nonlinear dynamical systems. Furthermore, the resonant feedback of the laser cavity coupled with the nonlinear pulse propagation generates new nonlinear dynamics. So far, complex soliton dynamics, such as soliton period-doubling bifurcations and chaos [1–4], soliton collapse [5], soliton group interaction [6] have been observed in the lasers. The soliton period-doubling and -tripling in fiber lasers were first documented by Tamura et al. [1]. Akhmediev et al. theoretically studied the soliton period-doubling in mode-locked lasers that are described by the complex Ginzburg–Landau equation [2]. In a previous paper we have first shown the complete soliton period-doubling route to chaos in a dispersion-managed fiber laser with large net negative cavity group velocity dispersion (GVD) [3], later we further reported soliton period-doubling in fiber lasers of around zero cavity GVD [4], where the generated pulses also displayed the dispersion-managed soliton features. Period-doubling of mode-locked pulses has also been observed in solid-state lasers operating in the negative cavity dispersion regime [7]. Recently Fernandez et al. have reported period-doubling of pulse repetition rate in a chirped-pulse oscillator with positive dispersion [8].

Although the dynamics of lasers of large positive cavity dispersion is still determined by the extended GLE, the formed soliton pulses in these lasers have distinct features from those of the solitons formed in lasers of negative cavity dispersion. While the solitons formed in lasers of negative cavity dispersion are dominantly a result of the balanced interaction between the cavity negative dispersion and the fiber nonlinear Kerr effect, the solitons formed in lasers of positive cavity dispersion are due to the spectral filtering of the limited gain bandwidth and the cavity nonlinearity. To distinguish these solitons were also called gain-guided solitons (GGSs) [9]. The GGSs are a localized, stable chirped nonlinear wave. Since in essence they are a kind of the GLE soliton, an interesting question would be whether the GGSs could still experience period-doubling bifurcation? In this paper, we give a positive answer to the question. We show the experimental observation of period-doubling of GGSs in an erbium-doped fiber (EDF) laser, despite of the fact that the GGSs have large chirp and broad pulsewidth. Numerical simulations also confirmed our experimental observation.

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The fiber laser used has a configuration similar to that reported in [10]. It is a typical dispersion-managed cavity that comprises 2.68 m EDF with GVD of about −32 (ps/nm)/km and peak absorption of 80 dB/m in the 1530 nm band, and 1.75 m standard single mode fiber (SMF), whose GVD is about 18 (ps/nm)/km. The net cavity dispersion was controlled by changing the length of the SMF. For the laser it was estimated 0.069 ps^2 at the wavelength of 1550 nm. The nonlinear polarization rotation (NPR) technique was used to achieve the self-started mode locking. The laser was pumped by a 1480 nm pump source and the generated pulses were output via a 10% fiber output coupler.

GGS operation, characterized by the steep spectral edges and pump power-dependent spectral bandwidth of the mode-locked pulses, was automatically obtained in the laser once the mode-locking was established. Starting from a stable GGS operation state, we then gradually increased the saturable absorption strength of the cavity. This was done through shifting the linear cavity phase delay bias away from the polarization switching point [10]. Accompanying the increase of the saturable absorption strength, the pump power was also carefully increased to maintain the stable GGS operation and simultaneously increase the pulse peak power. To a certain point of the pulse peak power it was observed that some spectral spikes suddenly appeared on the long wavelength side of the soliton spectrum as shown in Fig. 1a. However, the appearance of the soliton spikes did not affect the stable GGS operation. Fig. 1b and c shows the oscilloscope trace and

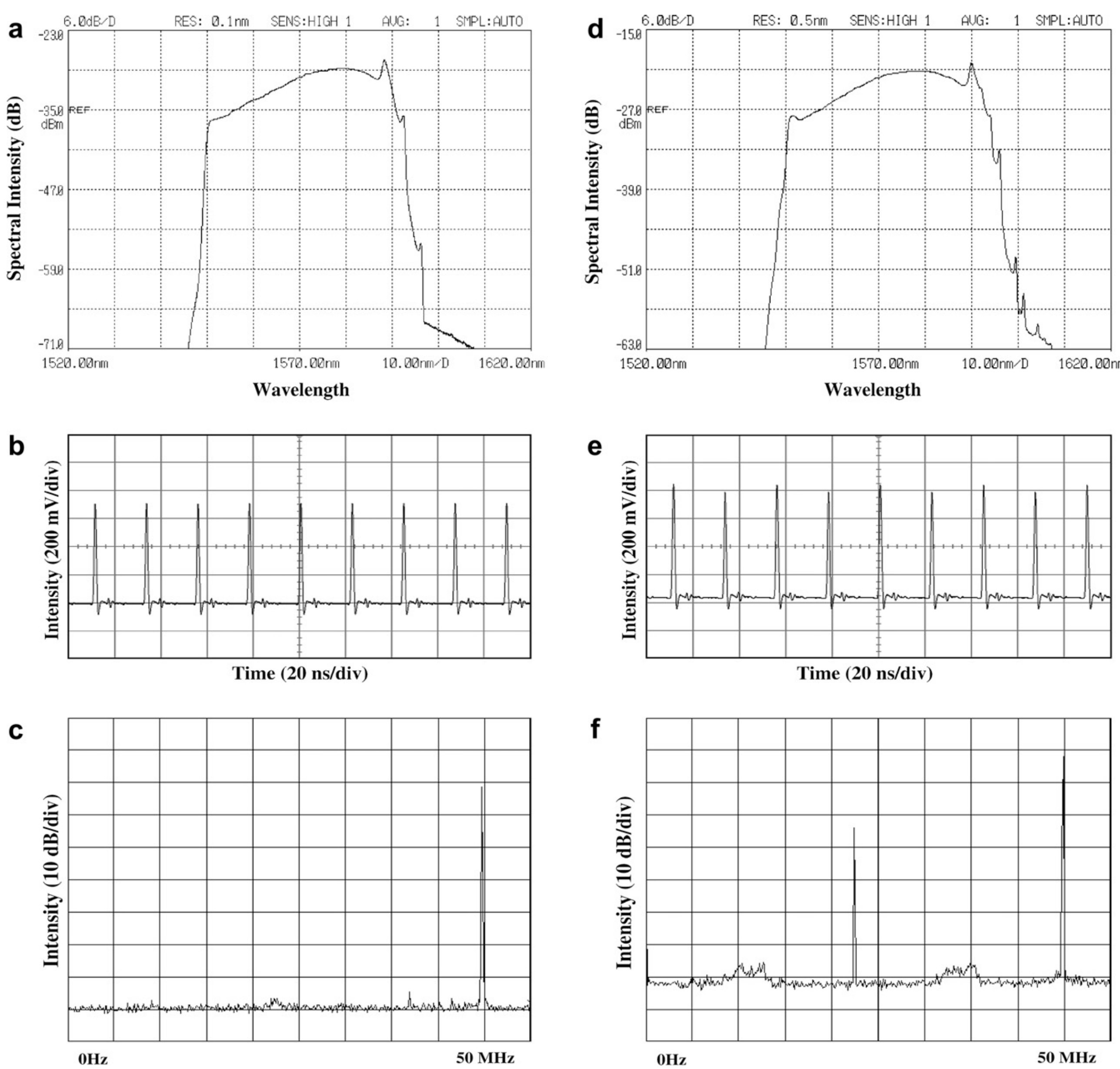

Fig. 1. Period-one/-doubling of GGSs in the laser. (a, d) Optical spectrum; (b, e) oscilloscope trace; and (c, f) RF spectrum.

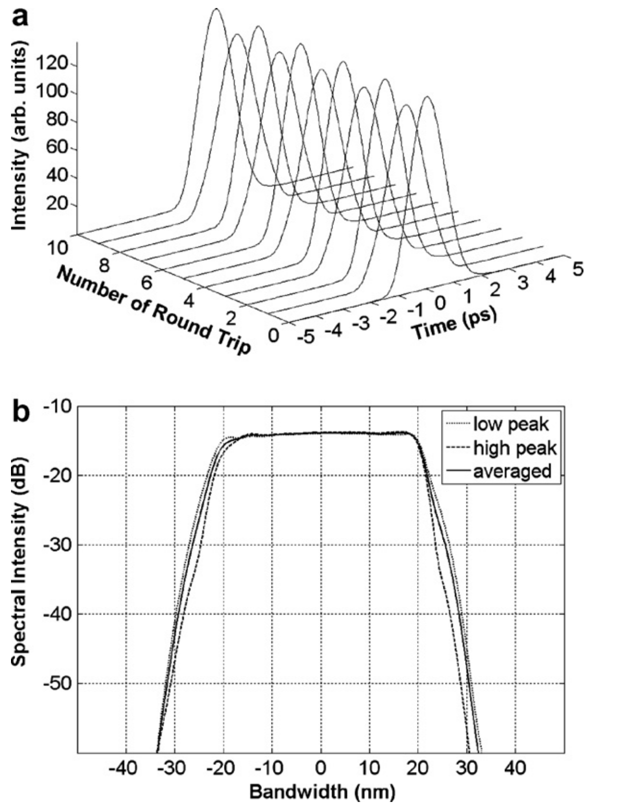

Fig. 2. Period-doubling of the GGSs numerically calculated. (a) Soliton evolution with the cavity roundtrips and (b) optical spectra of the soliton in two adjacent roundtrips and their average.

the RF spectrum measured immediately after the appearance of the spectral spikes. Obviously, the laser still emitted uniform pulses. The laser cavity length was about 4.5 m, which matched to the soliton repetition rate of 44.8 MHz shown in Fig. 1c. Based on autocorrelation measurements the GGSs of our laser have a pulse duration of about 3.18 ps if a Gaussian pulse profile is assumed. After the spectral spikes were obtained, if the pump power was further increased but with all other laser operation conditions fixed, a period-doubling bifurcation of the GGS was observed as shown in Fig. 1d–f. Associated with the period-doubling bifurcation, more spectral spikes appeared on the soliton spectrum (Fig. 1d). The period-doubling of the soliton is clearly visible on the oscilloscope trace, where after every two cavity round-trips the pulse energy returned, and on the RF-spectrum, where a new spectral component appeared at the position of half cavity fundamental repetition frequency. After period-doubling the average pulse width of the GGS became 2.65 ps. The above process was stable and repeatable in our laser. Nevertheless, no further period-doubling bifurcation but a noise-like state was observed when the pump power was further increased.

To gain insight into the experimental observation, numerical simulations were carried out to reproduce the dynamics of the GGSs. We have used the same model as reported in Ref. [10] and the following laser parameters:

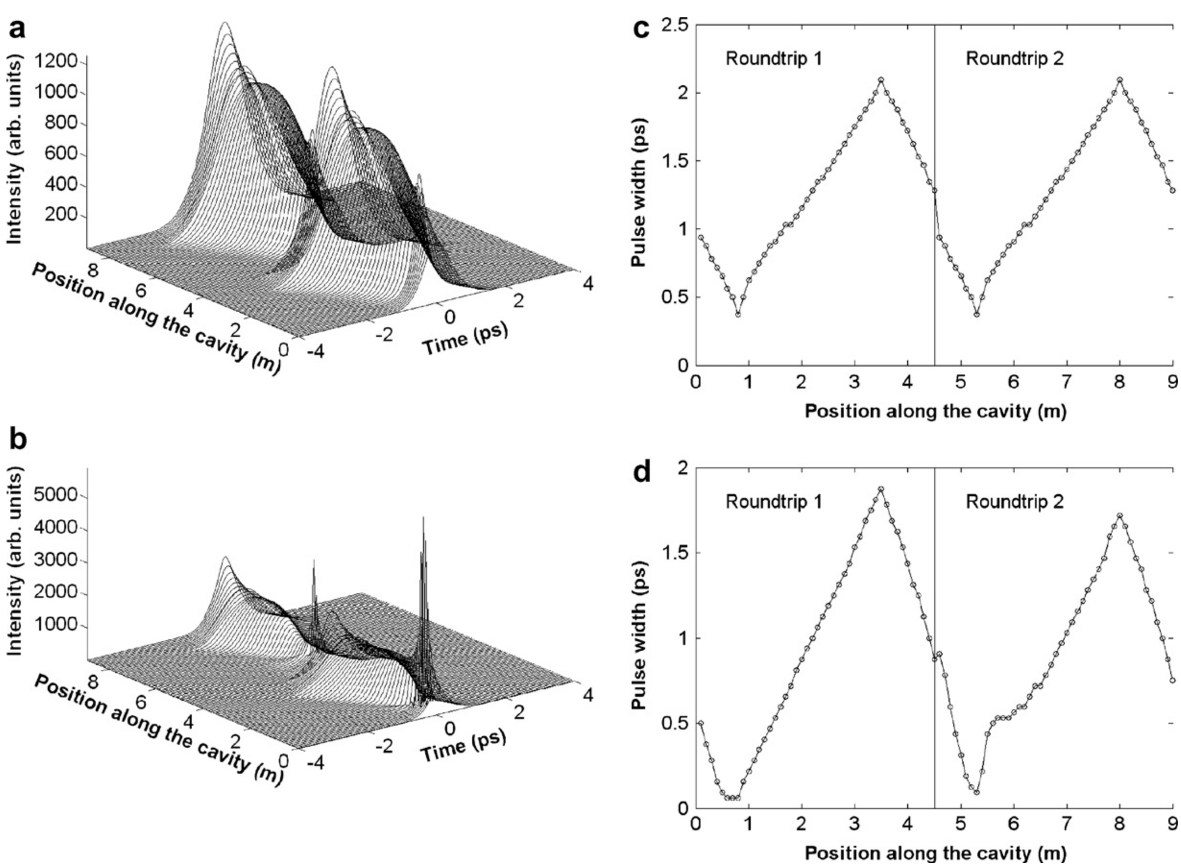

Fig. 3. Comparison between the soliton evolutions in cavity before and after the period-doubling bifurcation. (a, b) pulse evolution in time domain; (c, d) pulse width evolution; and (e, f) optical spectrum evolution in double cavity-length.

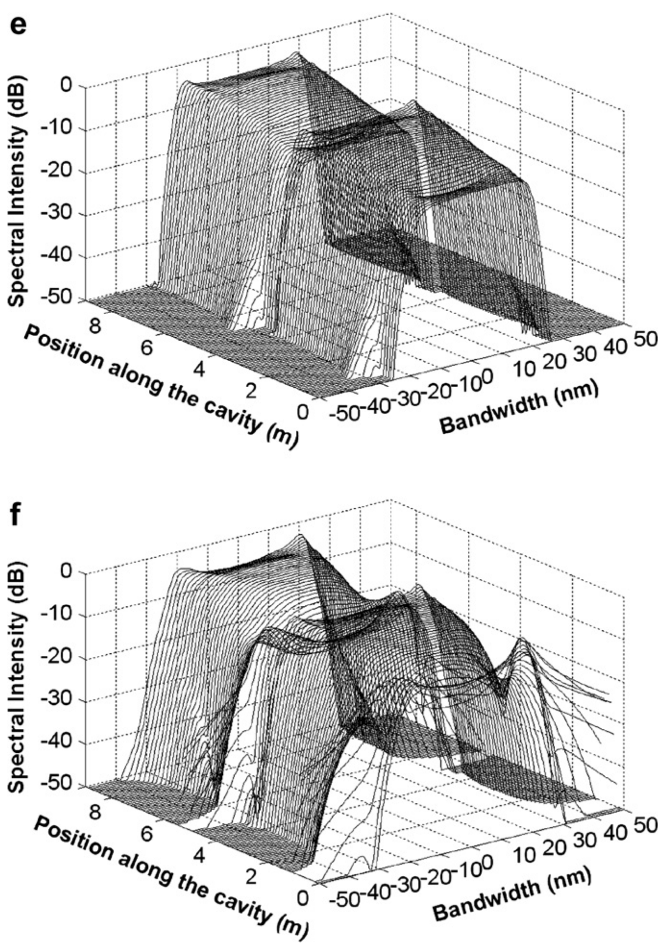

Fig. 3 (*continued*)

$\gamma = 3\ \mathrm{W}^{-1}\ \mathrm{km}^{-1}$; $K''_{\mathrm{SMF}} = -23.0\ \mathrm{ps}^2/\mathrm{km}$; $K''_{\mathrm{EDF}} = 40.9\ \mathrm{ps}^2/\mathrm{km}$; $K''' = -0.129\ \mathrm{ps}^3/\mathrm{km}$; $\Omega_{\mathrm{g}} = 16\ \mathrm{nm}$; gain saturation intensity $E_{\mathrm{sat}} = 1000\ \mathrm{pJ}$; cavity length $L = 0.8_{\mathrm{SMF}} + 2.7_{\mathrm{EDF}} + 0.3_{\mathrm{SMF}} + 10\%\ \mathrm{output} + 0.7_{\mathrm{SMF}} = 4.5\ \mathrm{m}$; cavity beat length $L_{\mathrm{b}} = L/4$; the polarizer orientation to the fiber fast axis $\Psi = 0.152\pi$; and the cavity linear phase delay bias $\mathrm{Ph} = 1.9\pi$.

Fig. 2 shows for example the numerically calculated period-doubling of GGSs when the pump strength was selected as $G = 4300$. Fig. 2a shows the evolution of the calculated GGSs with the cavity roundtrips. Period-doubling of the pulses is evidenced by that the pulse returns to its previous parameters at every two cavity roundtrips. Fig. 2b shows the optical spectra of the soliton in two adjacent roundtrips and the averaged one. Clear differences between them are visible. However, no obvious spectral spikes were obtained. We believe the absence of the spectral spikes could be caused by the parabolic gain profile approximation used in our simulations. From the experimental results the spikes only appeared on the edges of the spectrum, but where the parabolic gain profile artificially introduced large losses. Nevertheless, the numerical simulations have reasonably reproduced the essential features of the soliton period-doubling bifurcation, e.g. the simulated spectra have a flat and smooth top, and the spectral variations between the period-one and period-doubled states only occur on the edges of the spectrum, which are in agreement with the experimental observations and different from those of the soliton period-doubling observed in fiber lasers of negative cavity dispersion [3].

Fig. 3 shows a comparison between the evolutions of the GGSs in cavity before and after the period-doubling bifurcation numerically calculated. Fig. 3a and b shows the pulse evolution in the time domain along the cavity; Fig. 3c and d shows the corresponding pulse width variation along the cavity; Fig. 3e and f shows the evolution of the pulse spectrum corresponding to Fig. 3a and b, respectively. We note that Fig. 3 has shown pulse evolution in two cavity roundtrips in order to display the period-doubling effect. With all other parameters fixed period-1 state could be obtained in a large pump strength range. In a period-1 state the chirped GGS is compressed in the SMF segments. The stronger the pump strength, the larger is the chirp accumulated in the EDF, and consequently narrower pulse and higher pulse peak power is obtained in the SMF. After that the pulse peak power is beyond a certain value, period-doubling of the pulse occurs. Numerically we found that in a period-doubled state, the GGS may be de-chirped to a transform-limited pulse in the SMF, and remain the shortest pulse width until entering the EDF as shown in Fig. 3d. However, a pedestal also associates with the compressed pulse, which could be understood as a result of the pulse breaking.

In conclusion, we have experimentally observed period-doubling of the GGSs in a fiber laser and numerically reproduced the result. Although a GGS has completely different formation mechanism and properties from those of the solitons formed in fiber lasers of negative cavity dispersion, it can still experience period-doubling bifurcation. Our result shows again that period-doubling could be an intrinsic feature of all mode-locked lasers, its appearance is independent of the features and properties of the mode-locked pulses.

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